A Modeling Assessment of the Thermal Regime for an Urban Sport Fishery

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ABSTRACT / Water temperature is almost certainly a limiting factor in the maintenance of a self-sustaining rainbow trout (*Oncorhynchus mykiss*, formerly *Salmo gairdneri*) and brown trout (*Salmo trutta*) fishery in the lower reaches of the Cache la Poudre River near Fort Collins, Colorado, USA. Irrigation diversions dewater portions of the river, but cold reservoir releases moderate water temperatures during some periods. The US Fish and Wildlife Service's Stream Network Temperature Model (SNTEMP) was applied to a 31-km segment of the river using readily available stream geometry and hydrological and meteorological data. The calibrated model produced satisfactory water temperature predictions (R^2 = 0.88, $P < 0.001$, N = 49) for a 62-day summer period. It was used to evaluate a variety of flow and nonflow alternatives to keep water temperatures below 23.3°C for the trout. Supplemental flows or reduced diversions of 3 m^3/sec would be needed to maintain suitable summer temperatures throughout most of the study area. Such flows would be especially beneficial during weekends when current irrigation patterns reduce flows. The model indicated that increasing the riparian shade would result in little improvement in water temperatures but that decreasing the stream width would result in significant temperature reductions. Introduction of a more thermally tolerant redband trout (*Oncorhynchus* sp.), or smallmouth bass (*Micropterus dolomieui*) might prove beneficial to the fishery. Construction of deep pools for thermal refugia might also be helpful.

The Poudre River Trust, in cooperation with Trout Unlimited and the City of Fort Collins, Colorado, USA, has been working on a plan for the establishment and maintenance of a sport fishery in the Cache la Poudre River at Fort Collins (Pitts 1988). The plan is multifaceted, one element being the analysis of fishery potential and hydrology. A related, but separate, planning effort involves the study of this river corridor for possible federal designation as a National Recreation Area (Leaf, no date). These planning efforts give attention to recreation, water quality, floodplain development, and flood control.

Both streamflow and water temperature are thought to be limiting factors in establishing a self-sustaining sport fishery in the lower reaches of the Cache la Poudre River. The flows in this river, especially near Fort Collins, are extensively manipulated during both summer and winter, primarily to support irrigated agriculture. Opportunities for flow manipulation by controlling agricultural depletions are extremely limited due to existing senior water rights. A proposed water storage reservoir above Fort Collins, however, offers an opportunity for flow enhancement through the city.

The quantity and timing of streamflow necessary to support a coldwater fishery is being addressed through an evaluation of habitat potential using components of the US Fish and Wildlife Service's Instream Flow Incremental Methodology (IFIM) (Bovee 1982). Components of IFIM are used to assess the physical habitat availability for fish based on such habitat attributes as stream depth and water velocity. Hydraulic simulations are used to quantify the relationship between these physical habitat characteristics and streamflow (Milhous and others 1989).

Stream temperatures in the Poudre River vary widely on a seasonal as well as daily basis, but temperatures alone cannot be isolated as the limiting factor to a cold-water fishery. Conspicuous disease problems or indisputable fish kills have not been documented. Nonetheless, water temperature cannot be ignored, given the dominance of the fish community by warm-water species and observed water temperatures exceeding known levels of exclusion for cold-water species. Understanding the existing patterns of stream temperature fluctuation and predicting temperatures under modified conditions was the goal for one component of the Corridor Management Plan.

The thermal evaluation centers on three objectives:

1. Assemble data for and calibrate a stream temperature model capable of predicting water temperature at unmeasured locations under existing water delivery conditions.

2. Simulate the changes in temperature that will result from changes in controllable factors affecting tem-

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perature. The specific factors are changing discharges, riparian shade, and channel structure, specifically stream width.

3. Assess the feasibility of creating water temperature conditions favorable to various species of fish.

Study Area

The Cache la Poudre River is a tributary of the South Platte in north central Colorado and is characterized by a snowmelt-dominated hydrograph. It flows from the continental divide through mountainous terrain onto the plains near Fort Collins, draining an area of 2735 km^2 (1056 mi^2). The mean annual flow is 11.1 m^3/sec (392 cfs), of which 90% is diverted (Leaf, no date). Transmountain and transbasin diversions and small headwater reservoirs supplement the flow during the summer to fall irrigation season. Once the river flows onto the plains, an extensive network of irrigation diversions and storage reservoirs virtually dewater several segments of the river, especially near Fort Collins. Many urban rivers have undergone stream channel enlargement and overall quality degradation (Hammer 1972, Klein 1975); the Poudre River is no exception.

Monthly flows are highly variable. June flows are near 28 m^3/sec (1000 cfs). May and July discharges are less than 5.66 m^3/sec (200 cfs). From August through April, the discharge is commonly between 0.22 and 1.41 m^3/sec (8–50 cfs). Groundwater inflow, overland irrigation return flow, and a few small tributaries provide some moisture to the otherwise dewatered channel during the low flow months.

The study area extended 30.9 km from the mouth of Poudre Canyon to Interstate Highway 25 near Fort Collins (Figure 1). Upstream from the canyon mouth is Seaman Reservoir, on the North Fork of the Poudre River. One water development proposal would create a mainstem reservoir that would inundate Seaman Reservoir and several kilometers of the mainstem. Just downstream from the mouth of the canyon, the river is supplemented by the 6.2-km (3.9-mi)-long Charles Hansen Canal, bringing cold (9°C) hypolimnetic water from nearby Horsetooth Reservoir. This 178 million m^3 reservoir is supplied by water from the adjacent Big Thompson River drainage to the south.

The 30.9-km study reach has 16 irrigation diversion structures, some of which are large enough to consume the entire flow, except at times of peak runoff. The diversions are countered by four small inflows, one of which comes from a wastewater treatment plant (WWTP).

The mountainous sections of the Poudre upstream from the study area support both wild and hatchery rainbow trout (*Oncorhynchus mykiss*, formerly *Salmo gairdneri*) and brown trout (*Salmo trutta*). Historical records document the lower section of the Poudre, from the mouth of the canyon to its confluence with the Platte River, as being productive trout waters at least in some years (Geffs 1938, Burnett 1965, Watrous 1976, R. J. Behnke, Colorado State University, personal communication). However, this low-gradient section is not known as a productive trout stream today, presumably due to flow alterations and water-quality conditions, including temperature. Although trout are found throughout the study area, the marginal population is composed of a few fish sheltered in deep, cool pools fed by groundwater. The white sucker (*Catostomus commersoni*) dominates the community.

Methods

Early stages of data collection centered on defining the thermal requirements for a coldwater fishery and searching for available water temperature measurements to confirm the supposition that thermal limits may be one factor limiting the fishery. Modeling steps included: (1) the mathematical representation of the river as homogeneous segments with respect to such attributes as width, riparian shading, and flows; (2) assembly of meteorological and hydrological data; (3) calibration of the temperature predictions with measured data; and finally (4) temperature prediction under altered flow, altered stream width, and altered vegetative conditions.

Thermal Requirements of Important Fish Species

Brown and rainbow trout have similar thermal tolerances. Temperature tolerances typically appear in the literature in two forms: one from laboratory studies on individual fish, and one documenting the presence or absence of populations in watersheds with known temperature extremes. Observations of self-sustaining trout populations have reported temperature thresholds between 21 and 24.1°C, with a mean of 23.3°C (Cherry and others 1977, Javaid and Anderson 1967, Hokanson and others 1977, Kaya 1971, Barton and others 1985, Hokanson and Biesinger no date). No distinction was made in this study among differing life-stage requirements for the two species.

Laboratory results suggest lethal temperatures for both species in the range of 25–27.2°C (Brungs and Jones 1977, Raleigh and others 1984, 1986). The US Environmental Protection Agency recommends a method for calculating the short-term maximum temperature for specific durations (Brungs and Jones 1977). These calculations often include a 2°C "safety

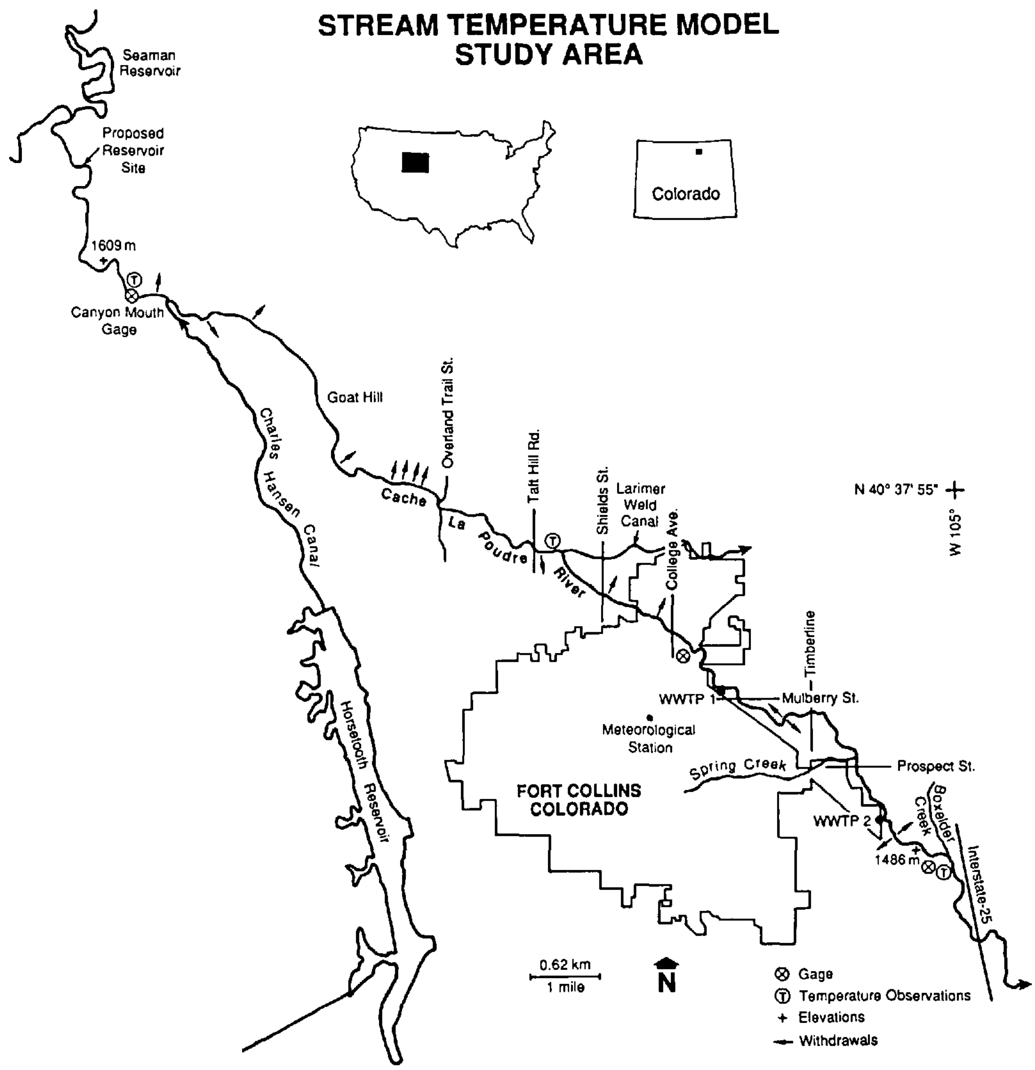

Figure 1. Cache La Poudre River near Fort Collins, Colorado. Gauging stations, temperature monitoring stations, meteorological station, major roads, canals, and wastewater treatment plants (WWTP) are shown.

factor," to be conservative (Coutant 1972). Based on these data for a 3-h period, a temperature threshold of 25.4°C for rainbow trout and 25.2°C for brown trout was calculated. The mean (25.3°C) was considered indicative of a threshold derived from this approach.

I believe that the lower of the two values is the most useful benchmark for a self-sustaining sport fishery. Laboratory-derived lethal limits do not adequately consider those indirect, nonlethal thermal effects such as competition with warm-water species. Therefore, a daily maximum temperature of 23.3°C was used as a goal to be achieved by increased flow or other means. Both values are indicated on the figures for comparison.

Available Water Temperature Data

Historical water temperature data for the Poudre consist largely of once-monthly US Geological Survey (USGS) grab samples and some measurements made by the Fort Collins Water and Waste Water Utility Departments. These data, although perhaps sufficient for detecting overall trends, were insufficient for characterizing the river's longitudinal thermal regime.[1]

Nearly continuous temperature measurements for 1987 were available from a study of the thermal effect of the proposed Grey Mountain Reservoir. These data, supplied by the local water conservancy district, included temperature monitoring at three locations: the mouth of Poudre Canyon (km 30.89), Hansen Canal

[1]This situation has changed with the addition of a continuous temperature recorder near College Avenue (km 14.0) in 1988.

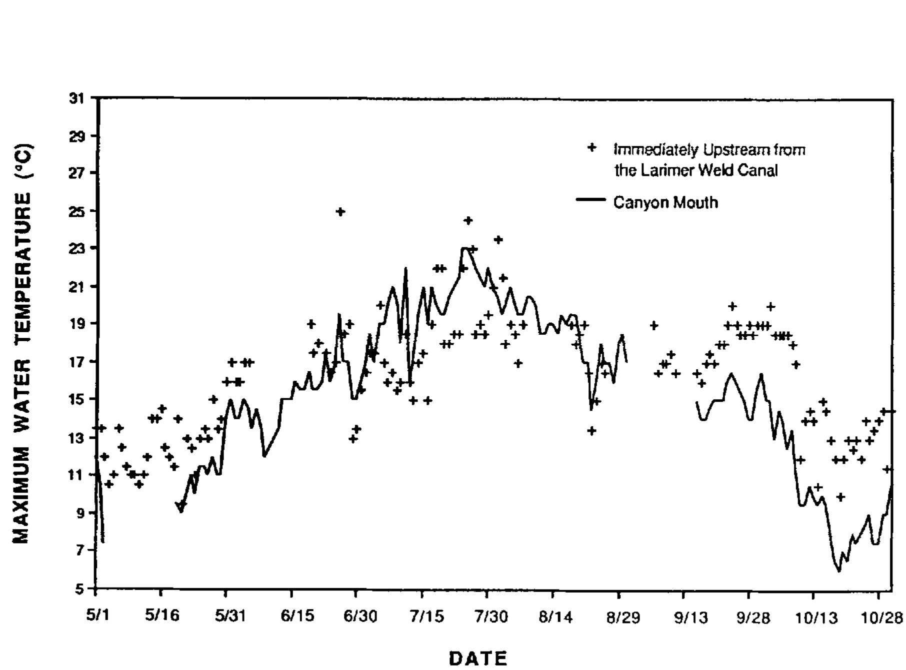

Figure 2. Maximum daily water temperatures recorded in 1987 at the mouth of Poudre Canyon and above the Larimer-Weld Canal. Missing values were the result of equipment malfunction.

outlet into the Poudre (km 29.33), and immediately above the Larimer-Weld Canal (km 17.55).

The in-river temperature data were analyzed to determine the period of the year most likely to result in elevated water temperatures. From these data (Figure 2), the period from 15 June to 15 August was chosen for more detailed analysis. However, there is another period in late September, after the Hansen Canal has stopped supplying cool reservoir water to the Poudre, that may have temperature problems. This period was considered a secondary priority and not included in this analysis.

Temperature Model Representation

The Stream Network Temperature Model (SNTEMP) of Theurer and others (1984) was used to analyze water temperatures in 1987. This one-dimensional heat-transport model predicts the daily mean and maximum water temperature as a function of stream distance and environmental heat flux. Net heat flux is calculated as the sum of heat to or from the atmosphere, direct solar radiation, convection, conduction, evaporation, streamside vegetation, streambed friction, and back-radiation from the water. The heat-transport model is based on a dynamic temperature–steady flow equation and assumes that all input data, including meteorological and hydrological variables, can be represented by 24-h averages. SNTEMP is applicable to a stream network of any size or order and runs on a desktop IBM-compatible computer.

SNTEMP is composed of several component models. The solar model calculates the amount of solar radiation penetrating the water. This is accomplished by supplying data on elevation, time of year, and latitude of the study area. The solar model first computes the radiation getting to the earth given the time of year. The latitude of the study area is used to calculate the site's sunrise and sunset times. Air temperature, relative humidity, and elevation are used to determine the attenuation of the radiation due to its travel through the earth's atmosphere. Cloud-cover data are used to further reduce the solar radiation. The direct solar radiation may also be intercepted due to local topography, which may further restrict the sunrise and sunset times. Radiation reaching the stream environment can be further reduced due to streamside vegetation. Finally, a certain amount of this short-wave radiation is reflected from the water's surface given the solar altitude angles.

The atmosphere itself is the source of long-wave radiation entering the water. Air temperature, cloud cover, and vapor pressure are used to determine the relative emissivity of the atmosphere. Streamside vegetation and topography are used as additional sources of long-wave radiation, depending on the air temperature and wind speed. Evaporation and convection are controlled by relative humidity, the difference between the air and water temperatures, wind speed, and atmospheric pressure, which in turn is controlled by elevation.

Conduction of heat to or from the streambed is a function of water temperature, ground temperature, and the relative insulation of the streambed. The stream gradient is used in combination with the discharge and width to calculate heat flux due to friction along the streambed. Finally, the water radiates heat back to the atmosphere in an attempt to reach equilibrium, a zero net heat flux. Turbulent mixing is assumed to mix the stream thoroughly both vertically and transversely during the downstream heat transport.

Other components of SNTEMP include: (1) meteorological corrections that predict changes in air temperature, relative humidity, and atmospheric pressure as functions of elevations within the watershed; and (2) regression aids that fill missing water temperature observations. Time steps ranging from one month to one day have been used in SNTEMP. A daily time step was chosen for this analysis.

The model was initialized with the continuous temperature measurements at the canyon mouth. Missing measurements (Figure 2) were filled with a standard linear regression algorithm (Theurer and Voos 1982). Temperatures of irrigation return flows and the small tributaries were assumed to be at thermal equilibrium. In addition to the continuous temperature measurements, the temperature model required data that described the meteorology, hydrology, and stream geometry of the study area.

Meteorology. Daily air temperature, wind speed, relative humidity, and solar radiation data were obtained from the Colorado Climate Center, an affiliate of Colorado State University. Because solar radiation data can be sensitive to instrument errors, an additional source of radiation data, available from the Fort Collins Water Utility Department, was used to double check the Climate Center data; no large differences were found. Percent possible sun (a surrogate for cloud cover) was calculated by adjusting mean values given in the Local Climatological Data Annual Summary (NOAA 1987) to correspond with the solar radiation data.

In addition to the 1987 data, long-term data for air temperature also were obtained from the Colorado Climate Center and from the CLIMATEDATA data base (Perry 1988). These data reinforced the selection of the 15 June–15 August period for expected temperature extremes in the river. During this season, air temperatures were at or above 32.2°C (90°F) for 19 days in 1987 and 22 days in 1988. Exceedence plots of the average maximum air temperature for the study period showed that 1987 temperatures were equaled or exceeded about 25% of the time (Figure 3).

Hydrology. The Fort Collins Water Utility Department supplied daily discharge estimates for 32 locations (hydrology nodes) from the mouth of the canyon to Interstate Highway 25. Their interest in these estimates stemmed from their need to calculate sewage treatment dilutions accurately. Data included flows in the river, amounts of diversions and returns, and lateral (groundwater) accretions between points of known flow. Data

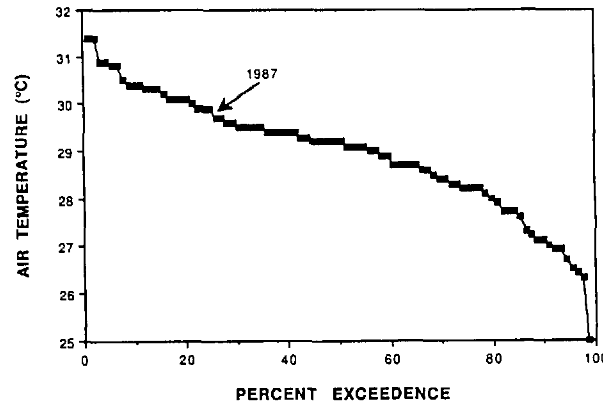

Figure 3. Exceedence plot of average maximum air temperatures for 15 June–15 August, compiled for 1900–1987. The summer of 1987 average (29.7°C) was equaled or exceeded about 25% of the time.

were supplied for June, July, and August 1986 and 1987. Figure 4 describes the linear structure of the river as used in the temperature model.

The only gauged flows came from the USGS stations at the mouth of the canyon, at Lincoln Street, and Boxelder Creek, as well as at the Hansen Canal outlet. Remaining discharges were calculated by mass balancing based on diversion amounts reported by irrigation companies and other water users. These relatively crude calculations resulted in some unexpectedly high and low flows near Waste Water Treatment Plant 2, and thus in the daily distribution of lateral flows (i.e., groundwater inflows to the river). This flow pattern was retained, however, because the available data could not support further refinement.

Stream geometry. Stream geometry data were collected from various sources. Stream widths as a function of flow were available from physical habitat data sets collected during 1987 (Nelson 1987). The study area was partitioned into homogeneous river segments based on width. This was accomplished by field observation and scrutiny of 1:400 scale aerial photographs provided by the County Planning Department.

SNTEMP may be used to calculate shading due to local topography and riparian vegetation. Clinometer measurements were used to determine the topographic horizon angles on both sides of the river; these are used by the model to calculate the local times of sunrise and sunset. The program calculates shadows produced by riparian vegetation from data describing the average tree height, crown diameter, and distance from the water's edge. The density of these shadows is also important and was estimated by measuring the proportion of sunlight intercepted by the vegetation. This was accomplished using a hand-held light meter and photo-

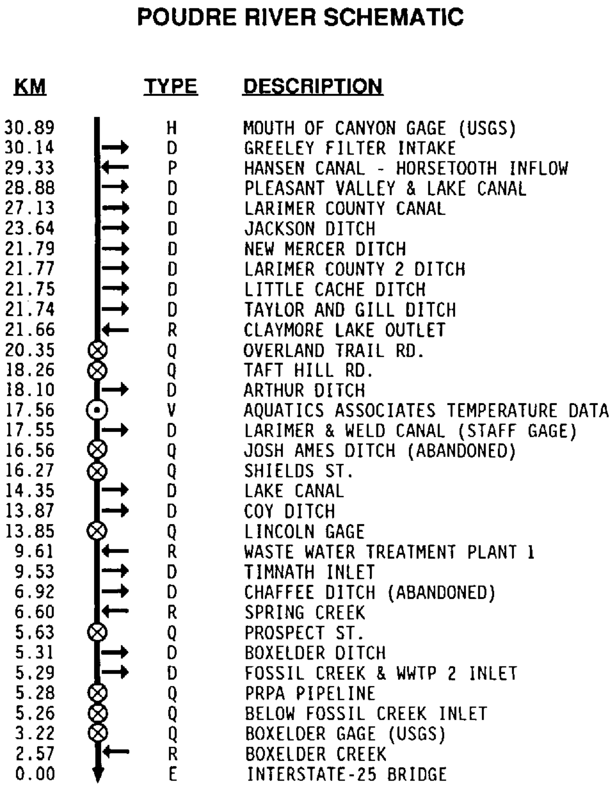

Figure 4. Schematic temperature model representation of the Cache la Poudre River. H = the head of the system, D = diversion structures, and R = return flows, Q = a point of known or estimated in-channel flow, V = a verification node where both flows and temperatures are known, and E = end of the system.

graphic gray card to measure light interception by the leaves and woody portion of the vegetation (Bartholow 1989). A value of 87% was used for the average riparian vegetation shading effect. Vegetative continuity measurements (the percent of streambank vegetated) for both sides of the river were made from aerial photographs. Different shade values were supplied for each of the river segments.

Stream distances, latitudes, and elevations were obtained from US Geological Survey 7.5′ topographic maps. Manning's n (a measure of the friction of water flowing over the streambed) values were obtained from Simons Li & Associates, a consulting firm studying the flood potential of the Poudre River for the Federal Emergency Management Act. They used a constant value of 0.035 for all segments.

Model Calibration and Verification

After data collection and data entry, several computer runs were made to calibrate the model's predictions with observed water temperature data. The model was given the measured water temperatures at the mouth of Poudre Canyon, the most upstream location, and it predicted temperatures at selected downstream locations based on its heat-flux and heat-transport equations.

The model's temperature predictions were compared with the continuous temperature measurements at two downstream locations: (1) above the Larimer-Weld Canal and (2) upstream of Boxelder Creek. The Larimer-Weld Canal data afforded a direct comparison with model predictions since it was collected during 1987. The Boxelder site provided only circumstantial verification as it was collected during 1988, but it was used because no other data describing water temperatures in the most downstream portion of the study area were available. Calibration of predicted to observed water temperatures was accomplished by adjusting the model's input variables (in this case relative humidity, stream width, and ground temperature), such that it produced accurate water temperature measurements at the downstream verification points. For this model, accuracy is defined as having three components: (1) high correlation between observed and predicted water temperatures, (2) minimal difference between the average of the observed and the average of the predicted values, and (3) minimal difference between individual daily observed and predicted temperatures.

The model's first water temperature predictions for the downstream locations were too low, indicating that not enough energy was entering the water. Using the advice from Bartholow (1989), relative humidity values were increased by 20% over recorded values to account for the humidity near the river. The stream width was also increased by 50% after my field measurements indicated that the physical habitat study sites had underestimated the width as a function of flow estimates for the river. I expect the previous field work did not adequately represent the wide, ponded areas behind diversion dams and areas of instream gravel mining.

One other parameter adjustment was made. The initial assumption that ground temperature, and thus groundwater inflow temperature, was equal to mean annual air temperature (9.1°C) did not appear to be consistent with records of ground temperature supplied by the Colorado Climate Center. Therefore, the temperature of a spring on Spring Creek, measured as 13.7°C in midsummer 1988, was used in the model.

Calibration was used to increase the accuracy and precision of the model predictions. The calibrated model produced results for mean daily water temperature above the Larimer-Weld Canal (Figure 5) that correlated well with temperature observations ($R^2 = 0.88$, $P < 0.001$, N = 49). On average, the model overpre-

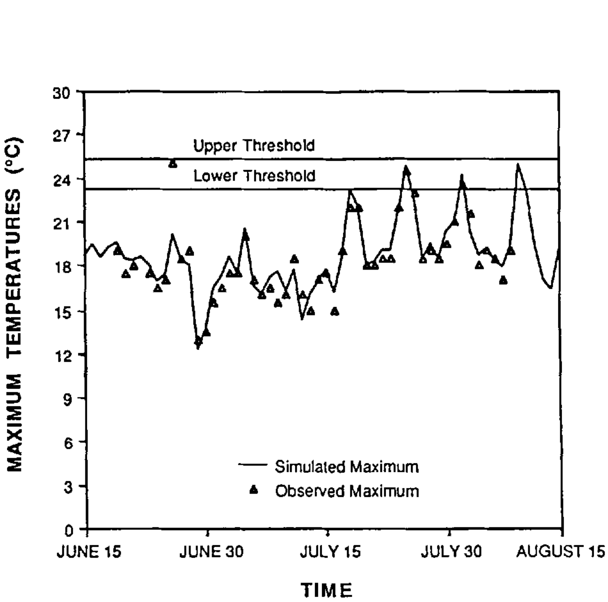

Figure 5. Results of final calibration run showing observed and simulated maximum daily water temperatures above the Larimer-Weld Canal in summer 1987.

dicted temperatures by 0.04°C, with 50% of the predictions lying within 0.47°C of the observed water temperatures. The maximum error for the 62 days was 1.8°C, excluding one day for which the thermograph was apparently out of the water due to near zero flow.

After calibration to mean daily temperatures, maximum daily temperatures were examined for both the Larimer-Weld Canal site at km 17.55 (collected in 1987) and the thermograph installed at the Boxelder site at km 2.57 (collected in 1988). Since the Boxelder data were collected during a different year, direct simulation was not possible. Therefore, the distributions of predicted and observed temperatures were informally compared. Means and standard deviations (Table 1) were judged close enough to preclude further calibration or data collection.

Results

After calibration, the model was used to evaluate the efficacy of both flow and nonflow alternatives in mitigating temperature extremes. It was convenient to isolate two representative days from the 62-day period to illustrate flow alternatives. The date 30 July 1987 was chosen because it displayed the hottest water temperature in the simulation period due to meteorological conditions. The date 8 August 1987 was chosen for its "hotness" due largely to the lack of cold-water release from the Hansen Canal, in concert with meteorological conditions. Although the temperatures overall were not higher than 30 July, they were much higher in the upper sections of the river. The following results refer to both days as examples.

Table 1. Maximum water temperature comparison (°C)

	Simulated	Observed
Larimer-Weld		
Mean maximum	18.78	18.50
Std. deviation	2.44	2.98
Boxelder		
Mean maximum	25.33	26.21
Std. deviation	2.08	0.96

Figures 6, 7, and 8 display the results of the alternatives evaluated, but they require some explanation prior to discussion of the results. Only temperatures at selected locations are shown on these figures. For example, stream temperatures actually increase slightly from the mouth of the canyon to the Hansen Canal. Mixing of the cold water from the canal immediately cools the stream. Displaying water temperatures only at certain locations, as in Figure 6a, depicts a misleading water temperature profile. A different phenomenon occurs at km 17.55, the Larimer-Weld Canal. This canal effectively consumes the entire river. Water downstream from this structure comes almost entirely from groundwater sources, and thus the model predicts a marked cooling immediately below the structure followed by gradual warming.

Flow Increments at Canyon Mouth

Since the proposed reservoir may be used to add flows to the river, several alternatives were examined by adding simulated increments of flow to the river at the mouth of Poudre Canyon. The increments tested were 1.4, 2.8, 5.7, and 8.5 m^3/sec (50, 100, 200, and 300 cfs). These increments were chosen because they were flow figures most often discussed as the increments required for suitable microhabitat in the river (Nelson 1987). It was assumed that any flow increment would be passed by all diversion structures and supplement all return and groundwater inflows. Alternative release temperatures from the proposed reservoir could have been simulated. However, the existing proposal calls for a multirelease outlet designed to minimize the effect on stream temperatures. Thus, the temperatures for flows at the mouth of the canyon were developed with a regression equation that included air temperature, humidity, and flow as the only significant variables.

The effects of these flow increments on maximum temperatures are best depicted graphically in Figure 6a and 6b, which show that large amounts of water are required to lower the maximum temperatures through-

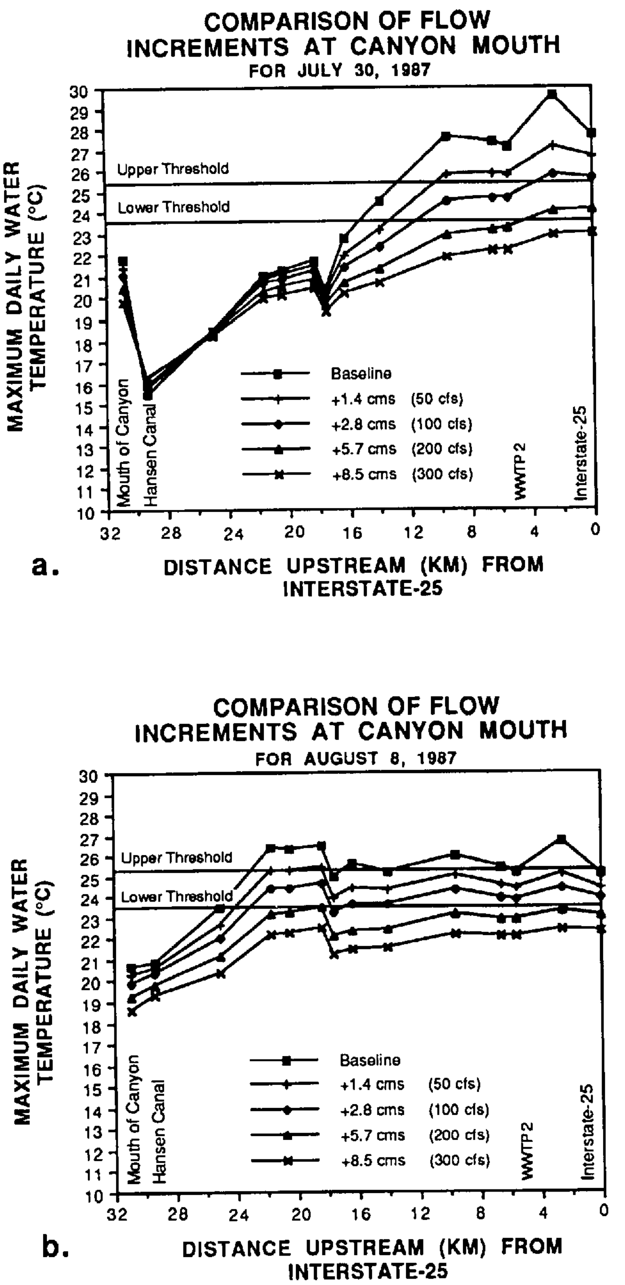

Figure 6. Longitudinal profile of temperatures resulting from the addition of water at the mouth of Poudre Canyon for 30 July 1987 (a) and 8 August 1987 (b).

out the study area. The baseline condition (original 1987 data) shows unsuitable temperatures in most of the study area, whereas a flow increment of 5.7 m^3/sec would enable suitable temperatures to a point near Waste Water Treatment Plant 2 below Prospect Street (km 5.29) on 30 July (Figure 6a). In contrast, the same flow increment would bring almost the entire study area into compliance with the temperature threshold on 8 August (Figure 6b).

Flow Increments from Hansen Canal

Simulated flow increments from Horsetooth Reservoir through the Hansen Canal are more effective than those from the mainstem, due to cool temperature of that release, which may be sustained throughout the growing season. The 30 July system response (Figure 7a) is virtually identical to that in Figure 6a, meaning that when the meteorological conditions are "hot," it does not matter whether the flow increment is from the Hansen Canal or from the mainstem—its going to warm to about the same level throughout the study area. However, the 8 August results (Figure 7b) show the beneficial effect of cold-water release; only about 4.2 m^3/sec would be required to maintain acceptable temperature conditions.

Nonflow Alternatives

Two nonflow alternatives were explored: doubling the riparian shade and halving the stream width (Figure 8a and 8b). Some floodplain protection measures being contemplated by the city may result in increasing the continuity of streamside vegetation. The baseline shading for all river segments averaged 13%; doubling the continuity of vegetation resulted in shading averaging 23%. However, doubling the shade, accomplished by doubling the continuity of streamside vegetation, resulted in little improvement in water temperatures; presumably the stream is too wide for shading to be a sensitive parameter.

The river's channel is broad, and even at low flow has large pool areas created behind each diversion structure and in areas used for gravel mining activities. The hypothetical halving of the width through channel manipulation resulted in substantial improvement in temperature conditions. However, it is unlikely that rehabilitation structures, such as wing deflectors or gabions (Barton and Winger 1973, Windell 1978), would be allowed due to the increased risk of flooding. In addition, reductions in stream width were not evaluated for changes in fish habitat and remain unknown.

Weekly Temperature Pattern

The College Avenue location (km 14.0) is about midway in the study area and a convenient location for summarizing the frequency of temperature extremes. Figure 9 illustrates the simulated sequence of maximum temperatures at College Avenue for the 1987 time window. Figure 10 takes a different perspective by showing the number of days when maximum temperatures

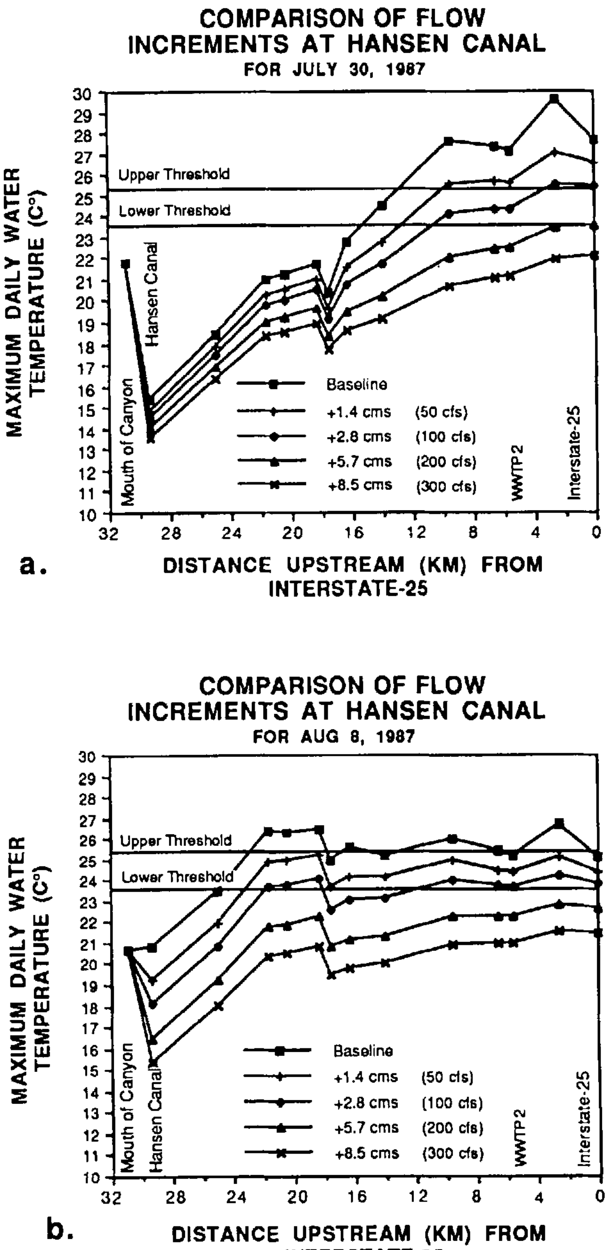

Figure 7. Longitudinal profile of temperatures resulting from the addition of cold water from Horsetooth Reservoir for 30 July 1987 (a) and 8 August 1987 (b).

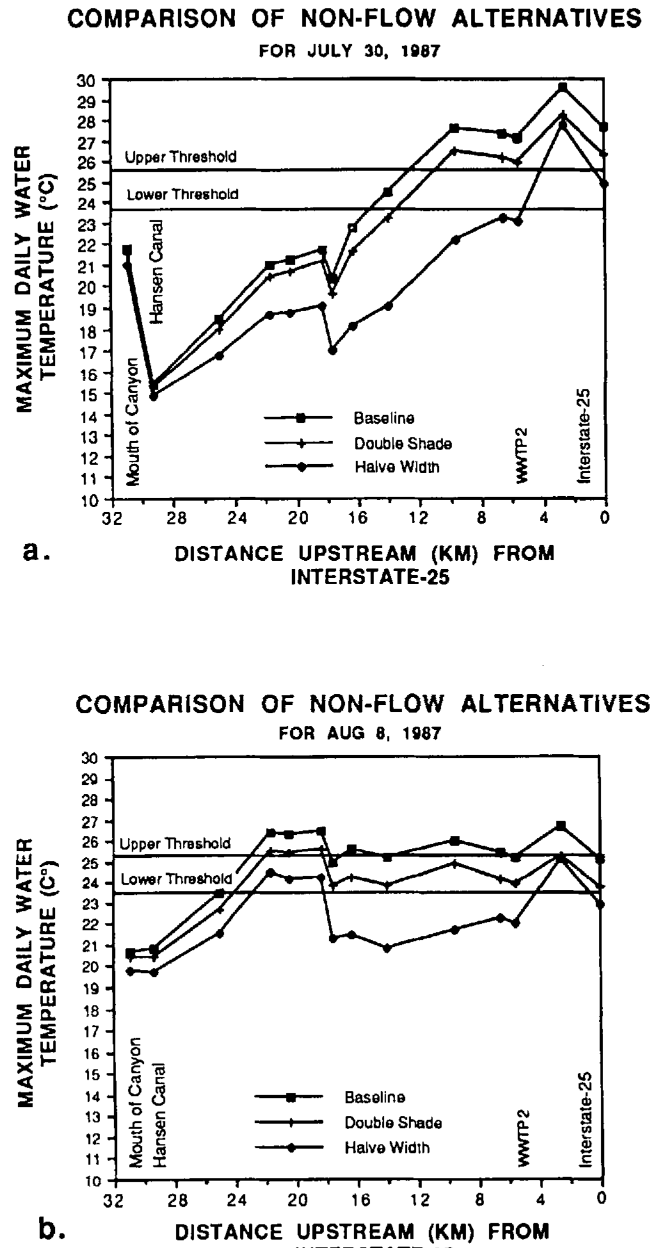

Figure 8. Longitudinal profile of temperatures resulting from nonflow alternatives for 30 July 1987 (a) and 8 August 1987 (b).

equaled or exceeded different levels. For example, the 23.3°C threshold was equaled or exceeded on 11 of the 62 days simulated under baseline conditions, or about 18% of the time.

Two noteworthy conclusions can be drawn from the College Avenue simulation results. First, there are two sets of three successive days when maximum temperatures reached 23.3°C or above: 24–26 July and 8–10 August. Although the criterion I used is for a single day only, the multiday periods are consistent with the failure of the river to support self-sustaining trout populations. Second, the same two three-day periods are, respectively, Friday–Sunday and Saturday–Monday. This is apparently due to the typical operations of the

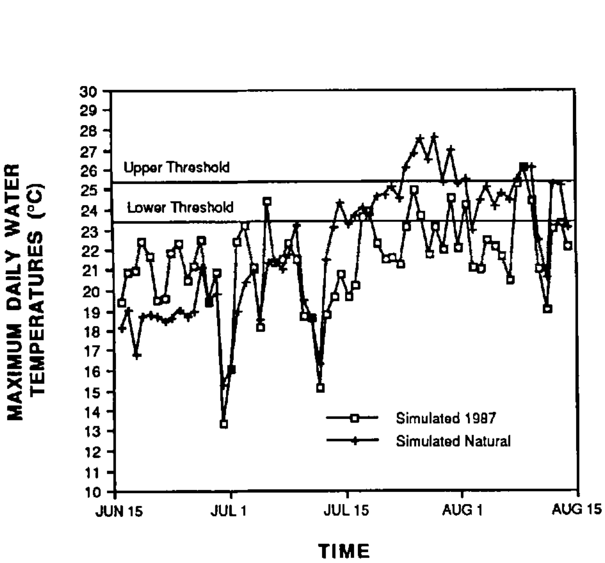

Figure 9. Comparison of maximum daily water temperatures for simulated 1987 and "natural" conditions at College Avenue. Natural conditions were created by eliminating all upstream water management influence and return flows, and allowing for a channel infiltration rate.

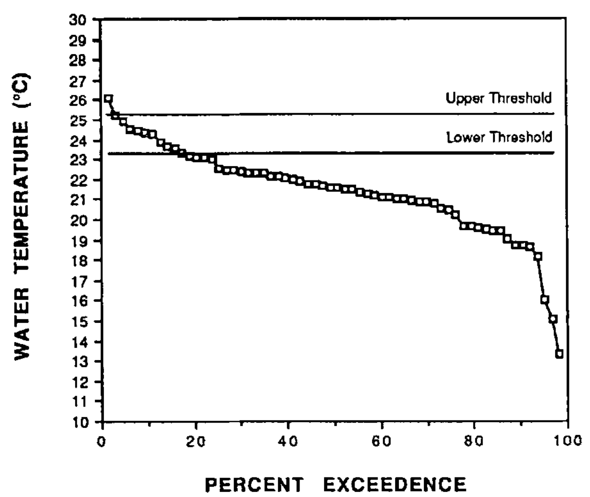

Figure 10. Exceedence plot for simulated maximum daily water temperatures at College Avenue (summer 1987).

Hansen Canal in which flows are reduced or eliminated during the weekends. In fact, of the 14 days exceeding 23.3°C, only three were not in the Friday–Monday period (Table 2).

Figure 11 shows the proportionate operation of the Hansen Canal for the 62-day period of 1987. It is clear that increased flows during the week have helped mitigate temperature extremes lower in the study area. It is unclear whether there is a possibility of cold shock when the reservoir release begins.

Table 2. Days of the week when temperatures exceeded 23.3°C

Day	No. of days
Friday	2
Saturday	4
Sunday	4
Monday	1
Other	3
Total	14

"Natural" Conditions

Because some water development began in the Poudre basin as early as 1860, it is difficult to get reliable information about predevelopment flows (instream or irrigation returns) or stream temperatures. Continuous flow measurements were recorded by USGS back to 1883, soon after transmountain importation began. "Natural" flow estimates, however, were available from the state water engineer (George Sievers, personal communication). These flows represented virgin river flows without reservoir supplementation, transmountain diversion, or irrigation diversion. The flows were simulated as if there were no diversion structures, but did include an expected infiltration (loss) rate of 0.00745 m^3/sec/m-wide/km (0.122 cfs/ft-wide/mi), estimated from Matlock (1965).

Under low-flow conditions, when most instream flow is from nonpoint returns, the amount of groundwater inflow is critical in determining temperatures. However, there is no simple method to estimate historical lateral flow (Carpenter 1916). There are indications that there was no significant amount of groundwater inflow before irrigated agriculture began. In fact, it may have taken up to 20 yr for seepage from agricultural operations to appear in significant amounts (Palos 1975). Therefore, all return flows were eliminated for the natural flow simulation. There is also some evidence that streamside vegetation differed in the 1800s (Burnett 1965), but this was not considered.

The results of this "natural flow" model indicated improved early-summer temperatures, but deterioration in conditions as the unsupplemented flows declined in late summer (also in Figure 9). Indeed, return flows from irrigation and wastewater treatment may result in higher flows and lower temperatures during the dry parts of the year than under virgin conditions. Although this brings into question some of the early reports of high-quality fishing, perhaps it was only the "good years" that were publicized. Alternately, a self-sustaining trout population may have been possible since unrestricted upstream movement in times of ther-

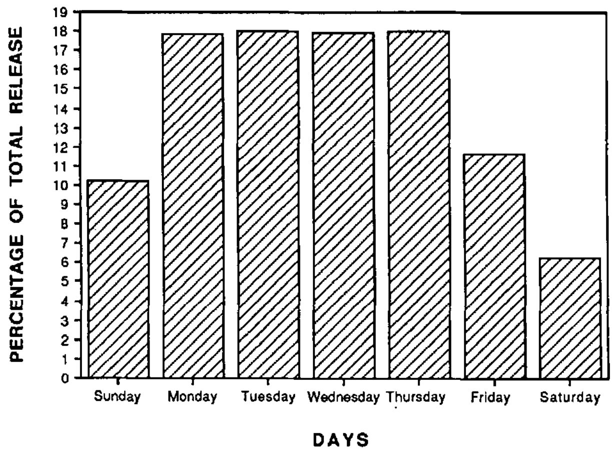

Figure 11. Daily proportion of cold-water releases from Horsetooth Reservoir for the summer of 1987. The sum of the percentages for all days is 100%. Reducing the release on the weekends contributed to several temperature extremes.

mal stress would have been possible (Kaya and others 1971, Clapp 1990). The existing diversion structures probably inhibit trout from seeking and finding thermal refuge at times of thermal maxima.

Conclusions

Model results have demonstrated that:

1. It is likely that a combination of flow and nonflow alternatives could be used on the hottest days to keep most of the river below temperature thresholds. However, conditions part way through this study area (downstream from Waste Water Treatment Plant 2 in this case) may never be satisfactory for rainbow or brown trout due to the thermal properties of the river.

2. Management for a self-sustaining trout fishery will require a mechanism to provide flow increments when warranted. Upstream cold-water releases offer more protection on more days during the hot season of the year. In particular, shifting part of the hypolimnetic release to the weekends would result in moderating temperatures through most of the study area.

3. Supplemental flows could be made available to offset thermal problems if a new mainstem reservoir is constructed. Without any change in the way the irrigation system now operates, judiciously applied additional flows of about 2.9 ± .25 m^3/sec (105 ± 9 cfs; 6240 acre-feet) would be required on an average of 30 days a year to maintain acceptable water temperatures down to the Waste Water Treatment Plant 2 throughout the 15 June to 15 August period. This amounts to about 2.2% of the Poudre's mean annual flow. It may be possible to reduce this amount by about one half if flows are provided in the afternoons only, but the SNTEMP model is incapable of addressing this question directly since it is a daily time step model.

Although the SNTEMP model may be used to illustrate some management alternatives, those alternatives may prove expensive or unfeasible. If cost-effective ways to mitigate temperature through flow management cannot be found, alternative fisheries might be considered. For example, establishing alternative races of trout, such as the redband (*Oncorhynchus* sp.), that may be slightly more heat tolerant (lethal temperatures ranging from 25.5 to 27.7°C; Sonski 1982, 1984) may be an option. Smallmouth bass (*Micropterus dolomieui*), which have temperature preferences in the 28–31°C range (Edwards and others 1983), may be another reasonable alternative species. Spring stocking coupled with a catch-and-release fishery in April and May, followed by a reasonable creel limit in June, might be another solution (Carl and others 1976).

Other mitigative techniques could be applied as well. Construction of deep pools between diversion structures may provide thermal shelter during extremely hot temperatures (Anderson and Miyajima 1975). These pools, preferably isolated from the warmer main channel flow, may provide lower temperatures and a reduction in the duration of temperature extremes. In addition, the existing diversion structures prevent upstream movement that may be desirable in times of thermal maxima. As these structures are replaced, some form of fish passage could be provided to facilitate movement.

Comments

Maximum temperatures are but one of the many potentially limiting factors to the establishment of a self-sustaining sport fishery on the Poudre River. Channel degradation and flow regime, especially in winter, may be equally important. Use of the SNTEMP model was not expected to determine the relative importance of limiting biological events. However, using this model did help answer the questions dealing with temperature during part of the year.

In this assessment I used a temperature model developed specifically for the use of readily available data (Theurer and others 1984). Data may be obtained from such diverse interests as city utility departments, weather stations, and other previously collected data not necessarily connected with stream temperature modeling. This study shows that simulation results of useful quality often can be obtained rapidly with little additional field work.

Literature Cited

Anderson, J. W., and L. Miyajima. 1975. Analysis of the Vincent Creek fish rearing pool project. US Department of the Interior Bureau of Land Management Technical Note 274. Denver, Colorado, 25 pp.

Bartholow, J. M. 1989. Stream temperature investigations: Field and analytic methods. Instream Flow Information Paper No. 13. US Fish Wildlife Service Biological Report 89(17), 139 pp.

Barton, D. R., W. D. Taylor, and R. M. Biette. 1985. Dimensions of riparian buffer strips required to maintain trout habitat in southern Ontario streams. *North American Journal of Fisheries Management* 5:364–378.

Barton, J. R., and P. V. Winger. 1973. Rehabilitation of a channelized river in Utah. Pages 1–10 *in* Proceedings of the 21st annual hydraulics division specialty conference, Montana State University, Bozeman. American Society of Civil Engineers, New York.

Bovee, K. D. 1982. A guide to stream habitat analysis using the Instream Flow Incremental Methodology. Instream Flow Information Paper 12. US Fish and Wildlife Service FWS/OBS-82/26, 248 pp.

Brungs, W. A., and B. R. Jones. 1977. Temperature criteria for freshwater fish: Protocol and procedures. US Environmental Protection Agency, Environmental Research Laboratory, Duluth, Minnesota. Report EPA-600/ 3-77-061, 129 pp.

Burnett, F. J. 1965. Golden memories of Colorado. Vantage Press, New York, 205 pp.

Carl, L. M., J. R. Ryckman, and W. C. Latta. 1976. Management of trout fishing in a metropolitan area. Fisheries Research Report No. 1836. Michigan Department of Natural Resources, Fishery Division, 29 pp.

Carpenter, L. G. 1916. Seepage and return waters, Part 1—General discussion and principles. Bulletin 180-Part 1. Colorado Agricultural College, Agricultural Experiment Station, Fort Collins, Colorado, 70 pp.

Cherry, D. S., K. L. Dickson, and J. Cairns, Jr. 1977. Preferred, avoided, and lethal temperatures of fish during rising temperature conditions. *Journal of the Fisheries Research Board of Canada* 34:239–246.

Clapp, D. F., R. D. Clark, and J. S. Diana. 1990. Range, activity, and habitat of large, free-ranging brown trout in a Michigan stream. *Transactions of the American Fisheries Society* 119:1022–1034.

Coutant, C. C. 1972. Biological aspects of thermal pollution II. Scientific basis for water temperature standards at power plants. *CRC Critical Reviews in Environmental Control* 3(1):1–24.

Edwards, E. A., G. Gebhart, and O. E. Maughan. 1983. Habitat suitability information: Smallmouth bass. US Department of the Interior, US Fish and Wildlife Service FWS/OBS-82/10.36, 47 pp.

Geffs, M. L. 1938. Under ten flags: A history of Weld County, Colorado. McVey Printery, Greeley, Colorado, 318 pp.

Hammer, T. R. 1972. Stream channel enlargement due to urbanization. *Water Resources Research* 8(6):1530–1540.

Hokanson, K. E. F., and K. E. Biesinger. No date. A national compendium of freshwater fish and water temperature data, Vol II, field validation of freshwater fish temperature requirements (research report). US Environmental Protection Agency, Environmental Research Laboratory, Duluth, Minnesota, 116 pp.

Hokanson, K. E. F., C. F. Kleiner, and T. W. Thorslund. 1977. Effects of constant temperatures and diel temperature fluctuations on specific growth and mortality rates and yield of juvenile rainbow trout, *Salmo gairdneri*. *Journal of the Fisheries Research Board of Canada* 34:639–648.

Javaid, M. Y., and J. M. Anderson. 1967. Thermal acclimation and temperature selection in Atlantic salmon, *Salmo salar*, and rainbow trout, *S. gairdneri*. *Journal of the Fisheries Research Board of Canada* 24(7):1507–1513.

Kaya, C. M., L. R. Kaeding, and D. E. Burkhalter. 1971. Use of a cold-water refuge by rainbow and brown trout in a geothermally heated stream. *Progressive Fish Culturist* 39(1):37–39.

Klein, R. D. 1975. Urbanization and stream quality impairment. *Water Resources Bulletin* 15(4):948–963.

Leaf, C. F. no date. National Recreation Area study: Cache la Poudre River, draft report. Shalkey Walker Assoc., Denver, Colorado, v.p.

Matlock, W. G. 1965. The effect of silt-laden water on infiltration in alluvial channels. PhD dissertation. University of Arizona, Tucson, Arizona, 102 pp.

Milhous, R. T., M. A. Updike, and D. M. Schneider. 1989. Physical habitat simulation system reference manual—version II. Instream Flow Information Paper No. 26. US Fish Wildlife Service Biological Report 89(16). v.p.

Nelson, P. C. 1987. Physical microhabitat versus streamflow relationships in the Cache la Poudre River, Fort Collins, Colorado. Poudre River Corridor Fishery Plan, Phase I Final Report. 8 pp. plus figures.

NOAA. 1987. Local climatological data annual summary with comparative values, Denver, Colorado.

Palos, G. 1975. Brief hydrologic history of the Cache la Poudre Basin between 1860 and 1970. M. W. Bittinger & Assoc. Inc., Fort Collins, Colorado, Ref: 433. 11 pp.

Perry, E. 1988. CLIMATEDATA user's manual, TD 3200, summary of the day-cooperative observer network. US West Optical Publishing, Denver, Colorado, v.p.

Pitts, T. 1988. Plan of action for Poudre River Corridor Fishery Plan. Tom Pitts and Assoc., consulting engineers. 47 pp.

Raleigh, R. F., T. Hickman, R. C. Solomon, and P. C. Nelson. 1984. Habitat suitability information: Rainbow trout. US Fish and Wildlife Service FWS/OBS-82/10.60, 64 pp.

Raleigh, R. F., L. D. Zuckerman, and P. C. Nelson. 1986. Habitat suitability index models and instream flow suitability curves: Brown trout. US Fish and Wildlife Service Biological Report 82(10.124), revised, 65 pp.

Sonski, A. J. 1982. Heat tolerance of redband trout. Annual proceedings of the Texas chapter of the American Fisheries Society, 15–16 October 1982. Kerrville, Texas, 5:66–76.

Sonski, A. J. 1984. Comparison of heat tolerances of redband, Firehole River rainbow trout, and Wytheville rainbow trout.

Annual proceedings of the Texas chapter of the American Fisheries Society, 6:27–35.

Theurer, F. D., and K. A. Voos. 1982. IFG's Instream water temperature model validation. Pages 315–318 *in* Conference on water and energy: technical and policy issues. American Society of Civil Engineers proceedings of the hydraulics conference, Pittsburgh, Pennsylvania, and Fort Collins, Colorado, 23–26 May and 23–27 June 1982.

Theurer, F. D., K. A. Voos, and W. J. Miller. 1984. Instream water temperature model. Instream Flow Information Paper 16. US Fish and Wildlife Service FWS/OBS-84/15, v.p.

Watrous, A. 1976. History of Larimer County, Colorado, 1911. Miller Manor Publications, Fort Collins, Colorado. Reprint of the 1911 edition, 513 pp.

Windell, J. T. 1978. Remaking a city trout stream. *Trout* 19(4):22–25.